Demonstration of advanced lumped parameter method in simulating Lotung Soil-Structure Interaction experiment

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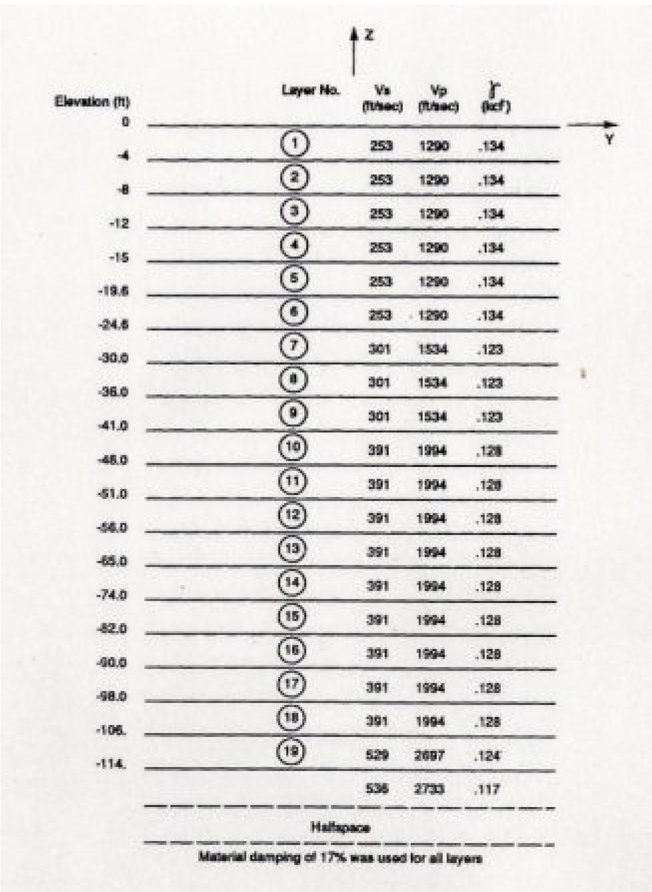
Introduction

This document provides a demonstration of how the advanced lumped parameter method performs in modelling the Lotung SSI (Soil Structure Interaction) experiment. Sufficient information for running a simulation of the experiment is (or was) available in the public domain through it being used to form the basis of example problem No 2 in the SASSI2000 User Manual (Ref 1). The experiment consisted of recording motion responses at various locations in a quarter scale model of a containment building (which included a mock-up of a steam generator equipment item on a support frame together with attached pipework) subject to an earthquake event. The example problem considers the E-W component of an earthquake event identified as 'LSST07' which occurred on 20th May 1986.

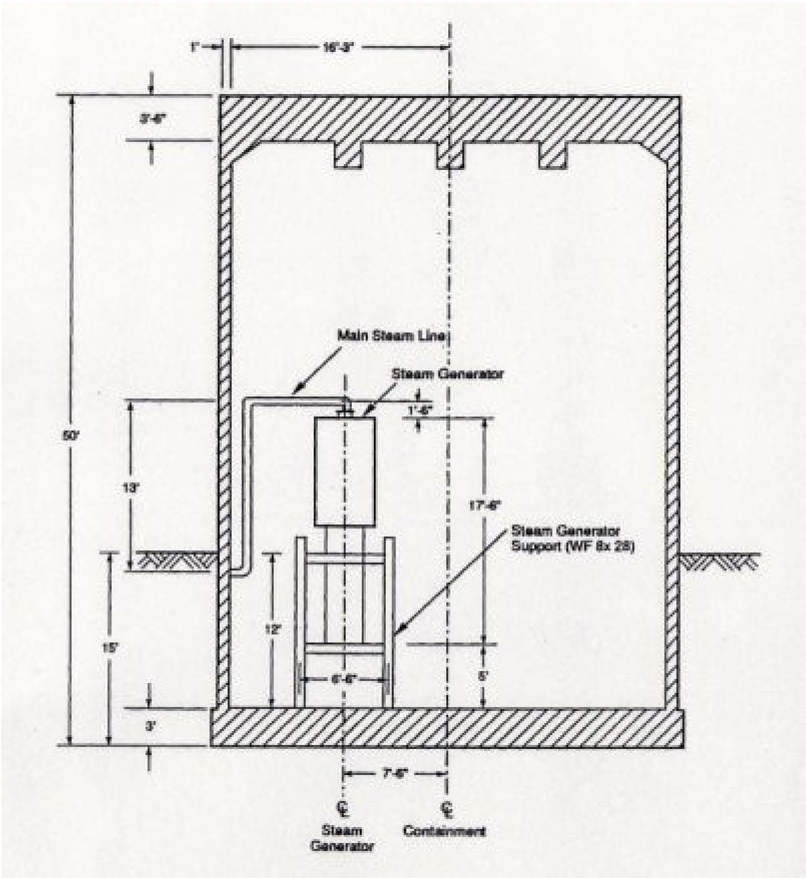
Basic problem details

The Lotung site profile properties (which are assumed to be at earthquake strain levels) and details of the containment building are shown in the figures below:



Elevation (ft)	Layer No.	Vs (ft/sec)	Vp (ft/sec)	γ (kcf)
0				
-4	1	253	1290	.134
-8	2	253	1290	.134
-12	3	253	1290	.134
-15	4	253	1290	.134
-19.6	5	253	1290	.134
-24.6	6	253	1290	.134
-30.0	7	301	1534	.123
-36.0	8	301	1534	.123
-41.0	9	301	1534	.123
-46.0	10	391	1994	.128
-51.0	11	391	1994	.128
-56.0	12	391	1994	.128
-65.0	13	391	1994	.128
-74.0	14	391	1994	.128
-82.0	15	391	1994	.128
-90.0	16	391	1994	.128
-98.0	17	391	1994	.128
-106.	18	391	1994	.128
-114.	19	529	2697	.124
Halfspace		536	2733	.117

Material damping of 17% was used for all layers



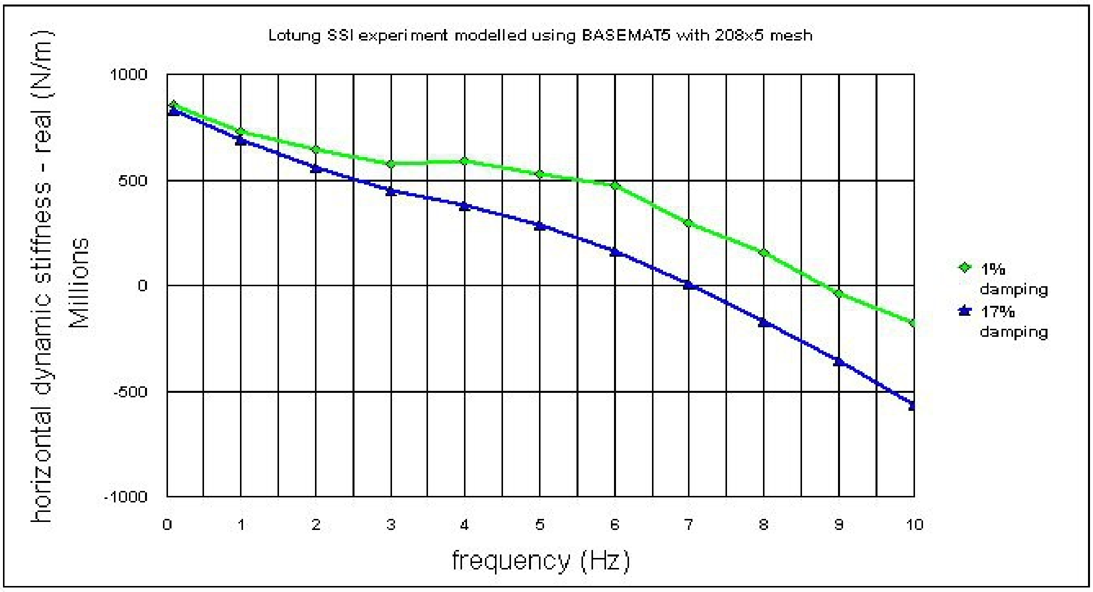
The site is extremely soft, probably softer than anybody would actually build a nuclear power plant on. The embedment ratio (embedment depth divided by foundation radius) of 0.87 is quite a bit higher than average for nuclear power plant buildings, so the benchmark problem favours SSI programs which are better at modelling embedment effects.

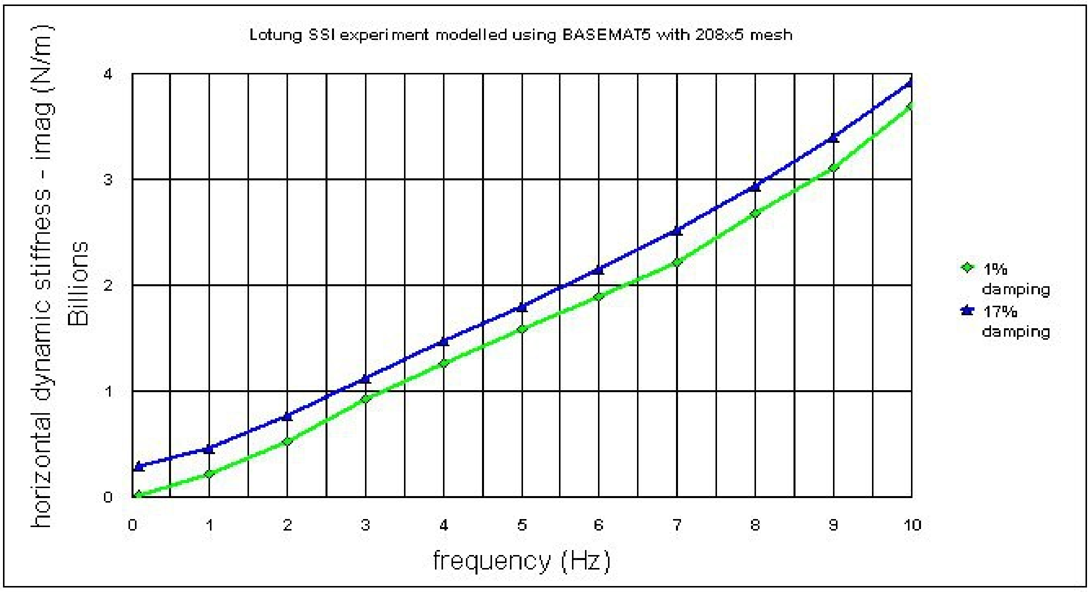
Generation of impedance functions

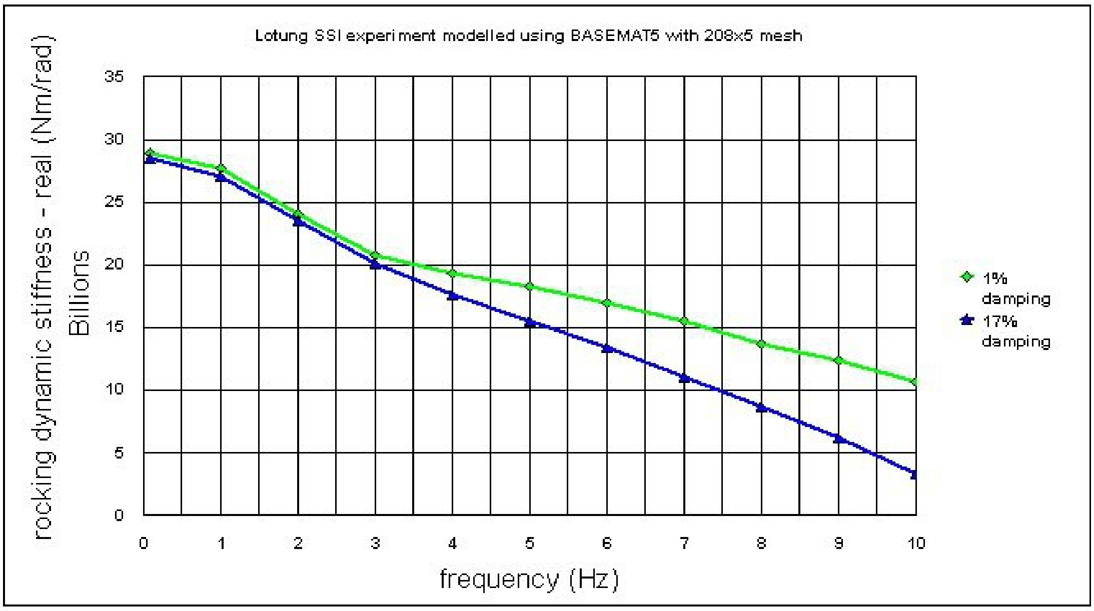
The site profile is defined as consisting of 20 layers in the SASSI analysis. In BASEMAT5 layers with identical properties can be combined into one layer (as a wavelength criterion is not used to determine layer thickness), so the profile can be reduced to 5 layers including the underlying halfspace.

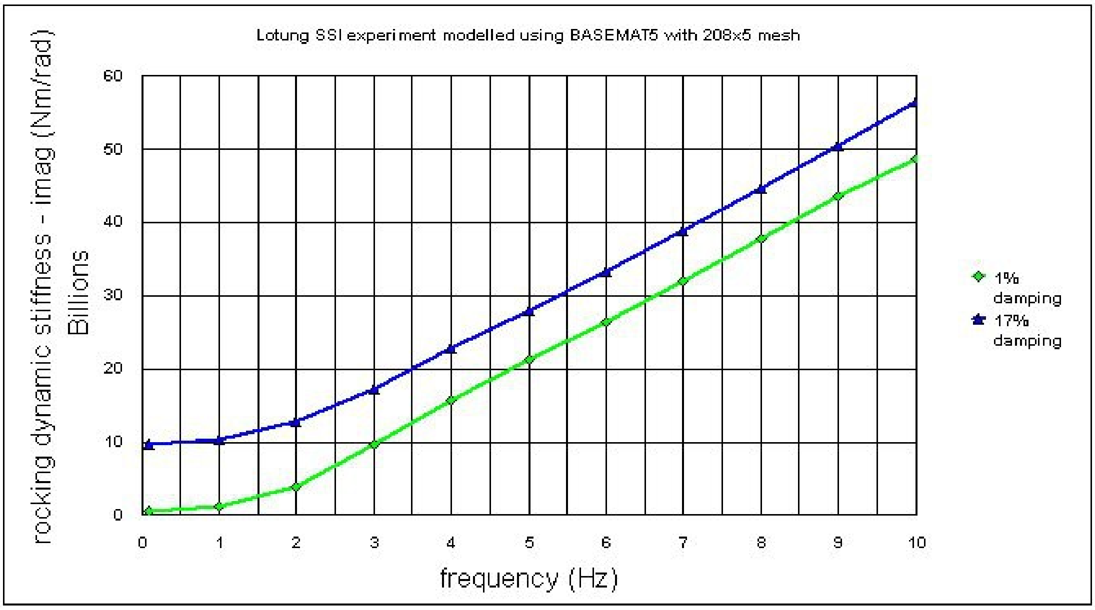
In the SASSI analysis 17% soil material damping is assigned to all layers. This value is almost certainly higher than a SHAKE deconvolution analysis of the site would give for the layers, suggesting the value may have been selected to give improved agreement with the test results (in these analysis versus test benchmark exercises, participants are sometimes allowed at some stage in the exercise to ‘tune’ the computer model to give better agreement with the test). For the BASEMAT5 analysis two soil material damping values were used : 17% as in the SASSI analysis and a much lower value of 1% (1% is intended to correspond to no material damping, but it is impractical to run an extremely low material damping value as this substantially increases the time taken to evaluate Greens functions).

The dynamic stiffness results (in SI units) for the embedded foundation for horizontal and rocking directions at 1% and 17% material damping are shown in the figures below. These impedance curves are based on fully welded contact between the embedded portion of the building and the adjacent soil. The soil material damping has an effect on the real component of dynamic stiffness as well as an effect on the imaginary component.









Curvefitting of Impedance Functions

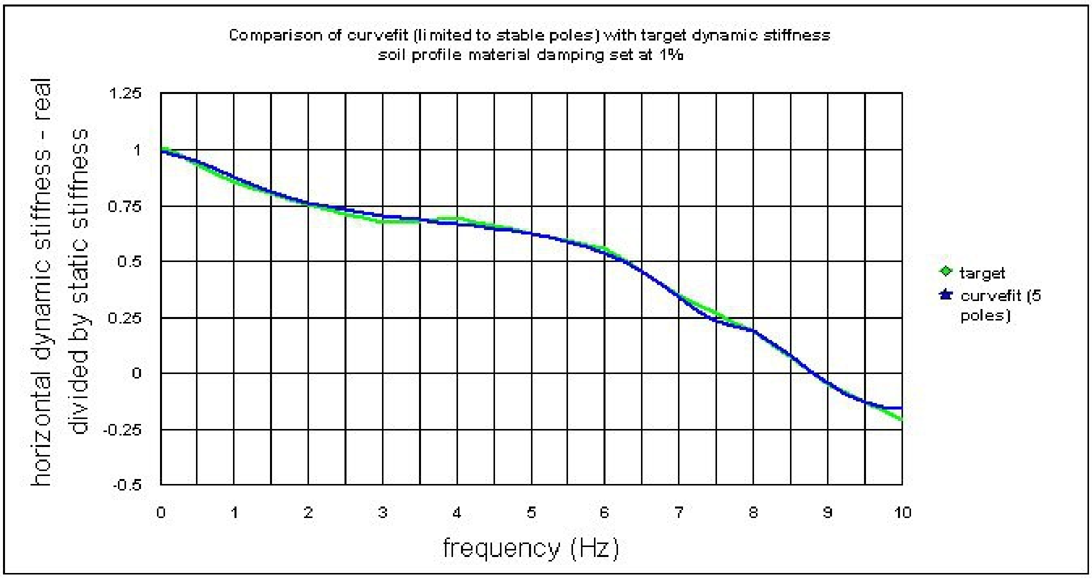
The impedance functions are curvefitted using the equation:

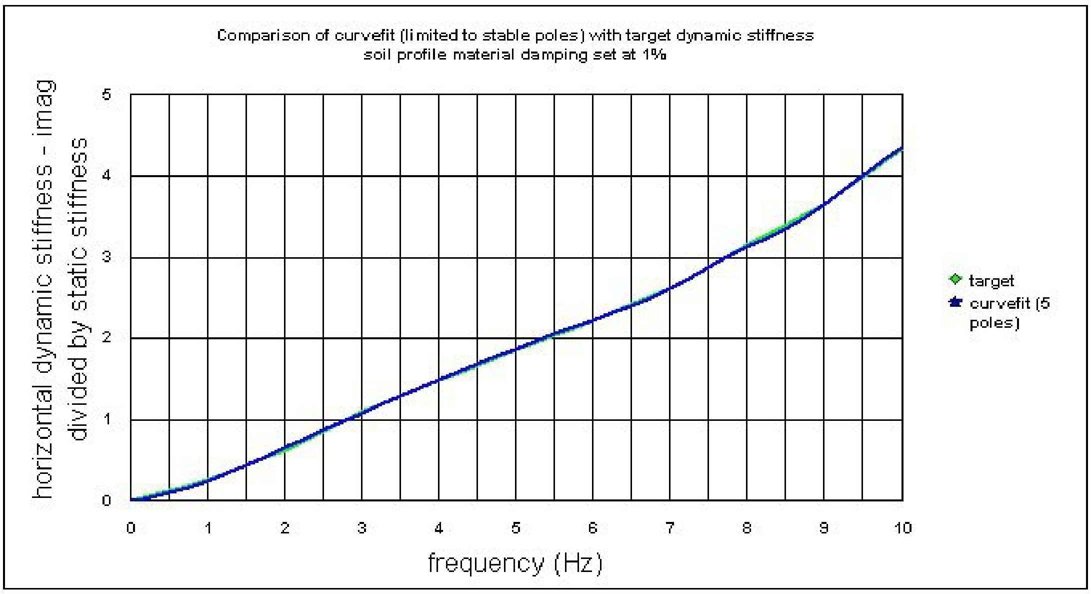
$$H(s) = \frac{c_1}{s-a_1} + \frac{c_2}{s-a_2} + \ldots + \frac{c_n}{s-a_n} + d + sh$$

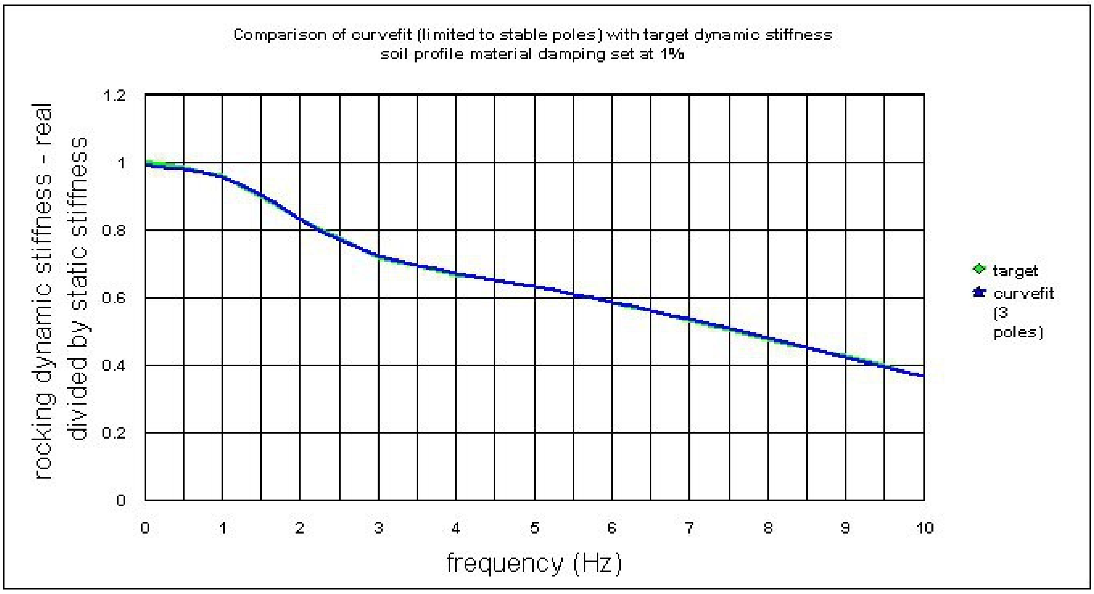
where $s = jw$, $c_1, c_2 \ldots c_n$ are complex number residues, $a_1, a_2 \ldots a_n$ are complex number pole location parameters, n is the number of poles, H(s) is the fitted value for dynamic stiffness and d + sh is the dynamic stiffness at high frequency. The curvefit parameters are selected to give a least square fit to the target dynamic stiffness data output by BASEMAT5. The curvefitting method used in LUMP_PARAM_SSI is a Fortran implementation of the iterative ‘vector fitting’ method (Ref 2).

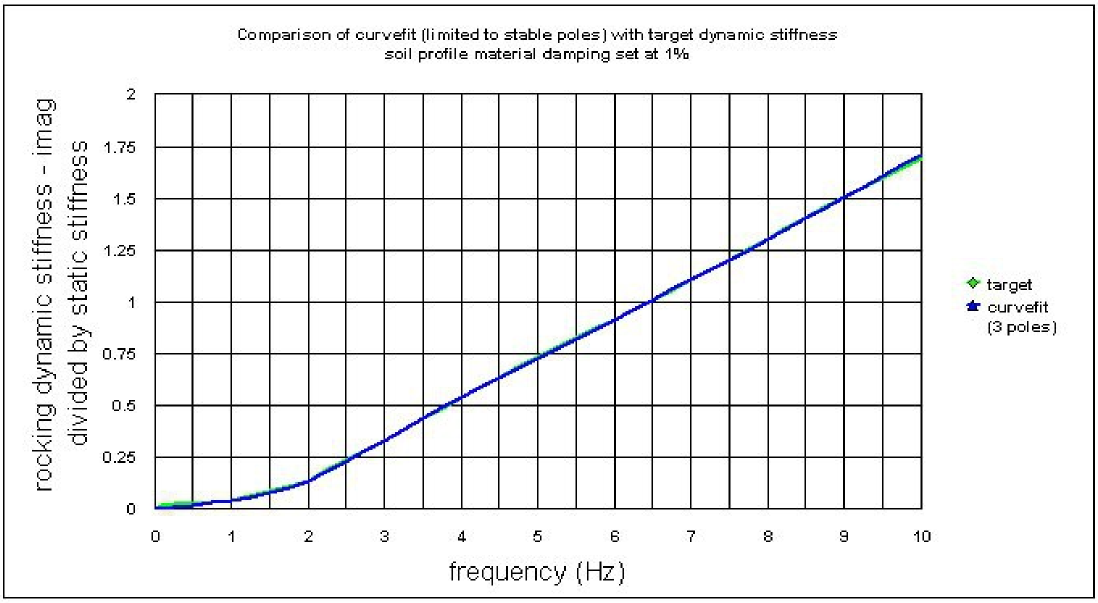
In the curvefitting, unstable poles have to be avoided because if converted to springs and dampers in the time domain they would cause the time history analysis to blow up. Unstable poles can be stabilised by reversing the sign of the real component of the pole parameter. In practice discarding an unstable pole was found to give similar curvefit results to stabilising an unstable pole.

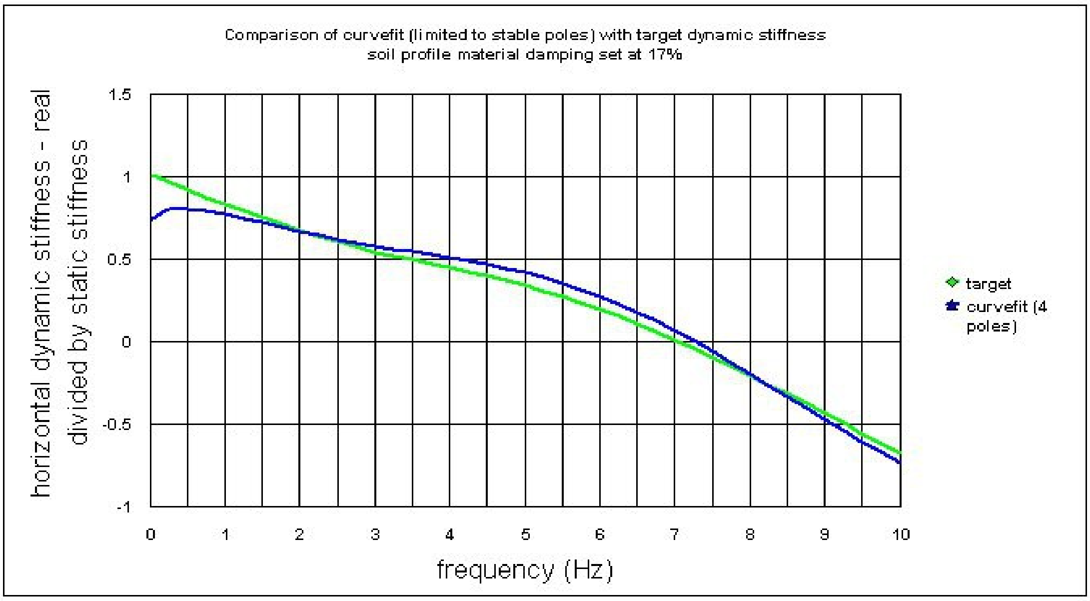
The figures below show that a very good match to the target dynamic stiffness curve is achieved for the horizontal and rocking directions at the 1% soil material damping level when limited to stable poles. The limitation of only using stable poles results in a less impressive but still reasonable match shown in the figures below at the 17% soil material damping level. Unstable poles seem to be required in particular to capture the imaginary component of dynamic stiffness at low frequency, suggesting that the unstable poles are being caused by the assumption of constant soil material damping with frequency, which is probably not a physically realistic assumption.

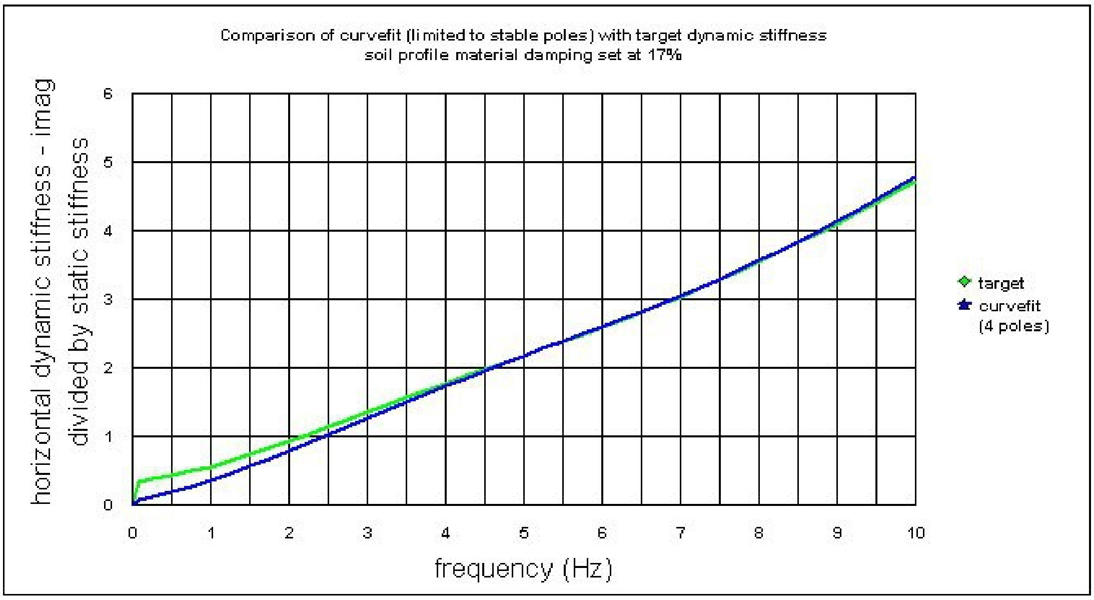


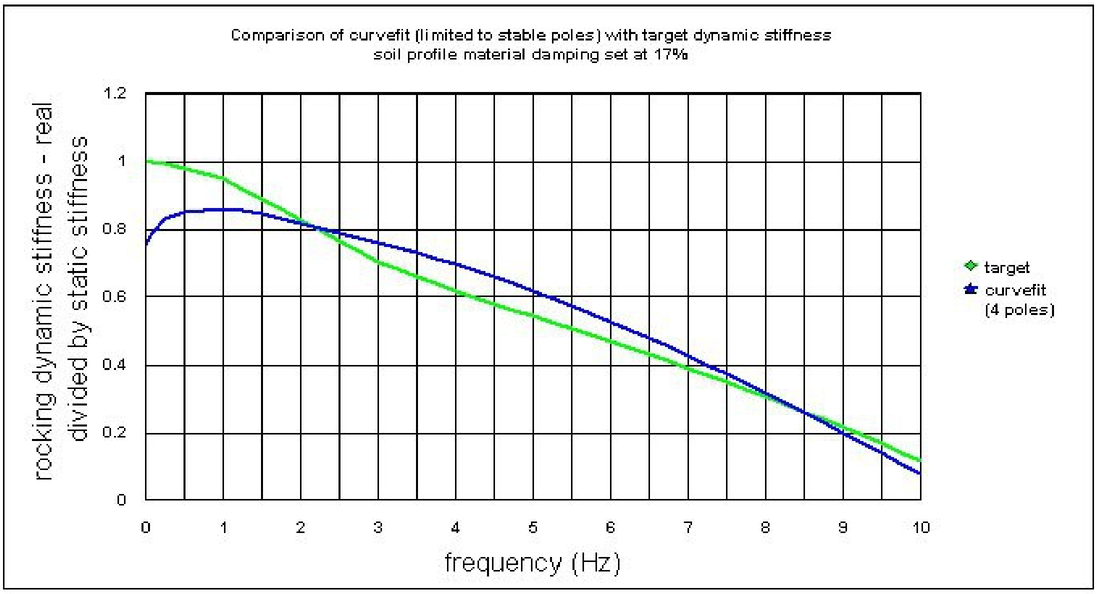


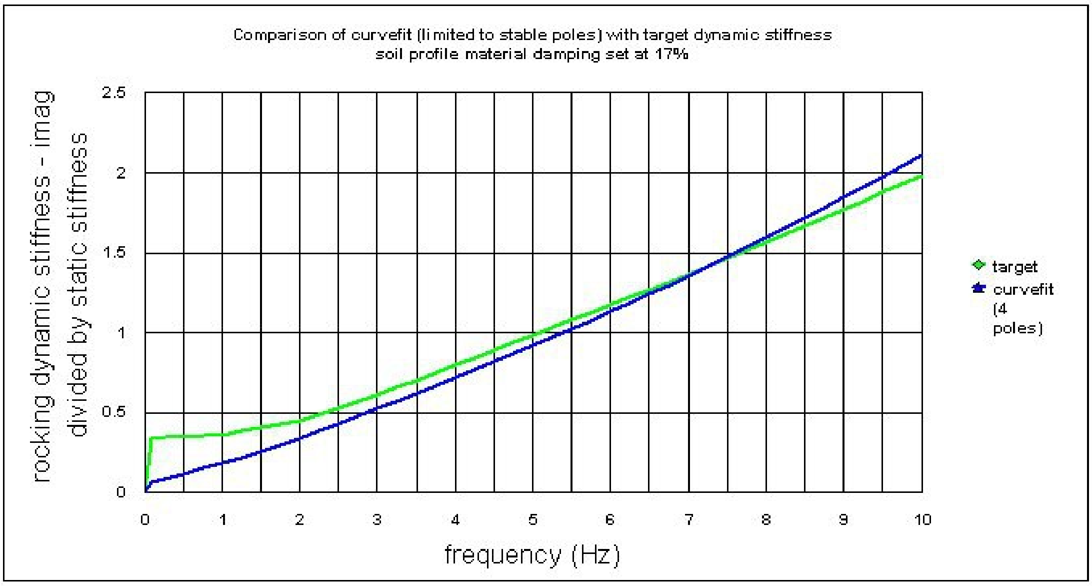

Comparison of curvefit (limited to stable poles) with target dynamic stiffness
soil profile material damping set at 1%
rocking dynamic stiffness - real
divided by static stiffness
1.2
1
0.8
0.6
0.4
0.2
0
0
1
2
3
4
5
6
7
8
9
10
frequency (Hz)
target
curvefit (3 poles)


Comparison of curvefit (limited to stable poles) with target dynamic stiffness
soil profile material damping set at 1%
rocking dynamic stiffness - imag
divided by static stiffness
2
1.75
1.5
1.25
1
0.75
0.5
0.25
0
0
1
2
3
4
5
6
7
8
9
10
frequency (Hz)
target
curvefit (3 poles)


Comparison of curvefit (limited to stable poles) with target dynamic stiffness
soil profile material damping set at 17%
horizontal dynamic stiffness - real divided by static stiffness
1.5
1
0.5
0
-0.5
-1
0 1 2 3 4 5 6 7 8 9 10
frequency (Hz)
target
curvefit (4 poles)


Comparison of curvefit (limited to stable poles) with target dynamic stiffness
soil profile material damping set at 17%
horizontal dynamic stiffness - imag divided by static stiffness
6
5
4
3
2
1
0
0 1 2 3 4 5 6 7 8 9 10
frequency (Hz)
target
curvefit (4 poles)





There is also a potentially significant non-zero dynamic stiffness coupling term (Khr) between the horizontal and rocking directions for an embedded cylindrical foundation. In principle this coupling term could be represented using a horizontal spring-damper network located at an offset distance above the base of the foundation. It was preferred to ignore the Khr term in this analysis as the term is often ignored in the more conventional versions of the lumped parameter SSI method, and including the term can lead to another potential numerical stability problem (where the time history analysis blows up) if the damping matrix associated with soil dampers is not semi-positve definite at all frequencies.

The pole and residue parameters for single (real) poles and complex conjugate pole pairs calculated in the curvefits are converted into spring and damper networks using another of the LUMP_PARAM_SSI programs. These springs and dampers can then potentially be used in a general purpose structural analysis program. For this Lotung study it was decided to use the popular earthquake engineering program DRAIN2DX to demonstrate that the advanced lumped parameter procedure is capable of being run in an ‘off the shelf’ structural analysis program. Note that some of the springs and dampers in the network have negative values, which may be rejected by some structural analysis programs (the negative springs are actually rejected by DRAIN2DX in a static analysis but are allowed through in a time history analysis and also a modal analysis).

Modelling of Lotung building

A DRAIN2DX model was set up for the Lotung building. The structural model differs from the SASSI2000 example problem No 2 in two areas:

(a) The SASSI model uses brick elements for the basemat, shell elements for the containment cylinder structure below ground and a stick model (beam elements) for the containment structure above ground. In DRAIN2DX a stick model is used over the full height of the building including the basemat.

(b) The internal structure model is simplified in DRAIN2DX to a 2D representation. The offset distance of the internal structure from the centre of the building is ignored and only the mass effect of the attached pipework is considered by lumping half the mass at the top of the steam generator. In the SASSI analysis the 3D geometry of the internal structure and associated pipework is represented.

The DRAIN2DX model input data was determined from relevant figures and tables in the SASSI2000 User Manual. In the case of the containment stick model, a model was developed directly from information given in the figures. Less information was available to develop a stick model of the internal structure from scratch, and so the SASSI internal structure stick model was adopted.

The DRAIN2DX building model has a total of 22 nodes with 10 nodes used for the networks of soil springs and dampers for the horizontal and rocking directions. Soil-structure interaction is represented by an extra ten degrees of freedom compared with a fixed base analysis. Dampers are represented in DRAIN2DX by a beta factor applied to a spring element.

The surface time history used as the ‘control motion’ in the SASSI analysis is applied at the base of the foundation (15 feet below the ground surface) in the DRAIN2DX analysis.

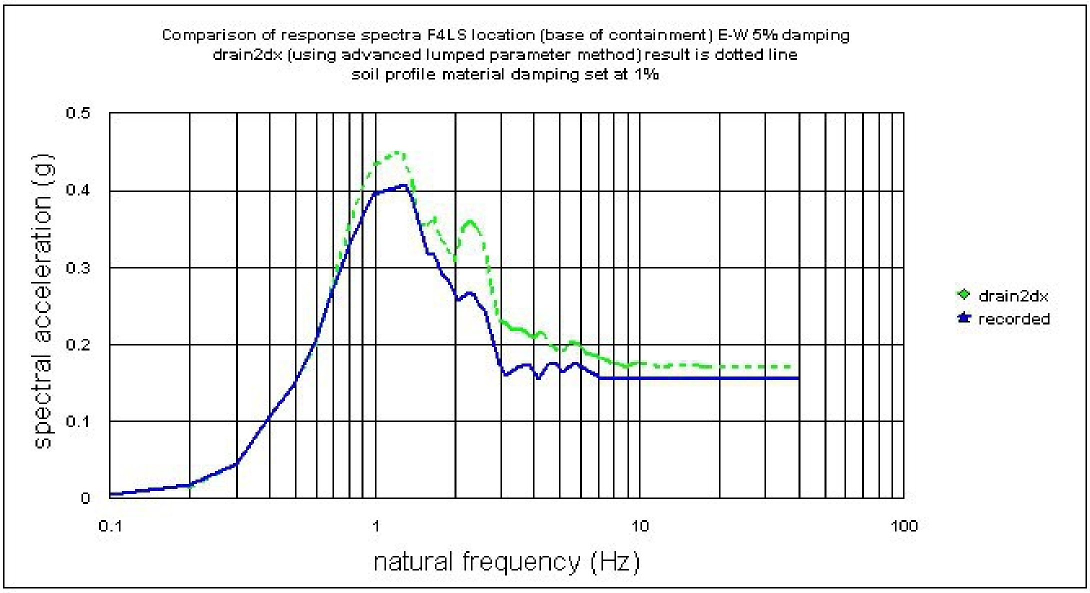
A modal analysis was performed in DRAIN2DX to determine a suitable timestep for the direct time history analysis and to provide some information on whether the model is behaving reasonably. The building model only had three vibration modes below 33 Hz, all actually below 10 Hz, which indicates that a timestep of 0.01 sec is acceptable.

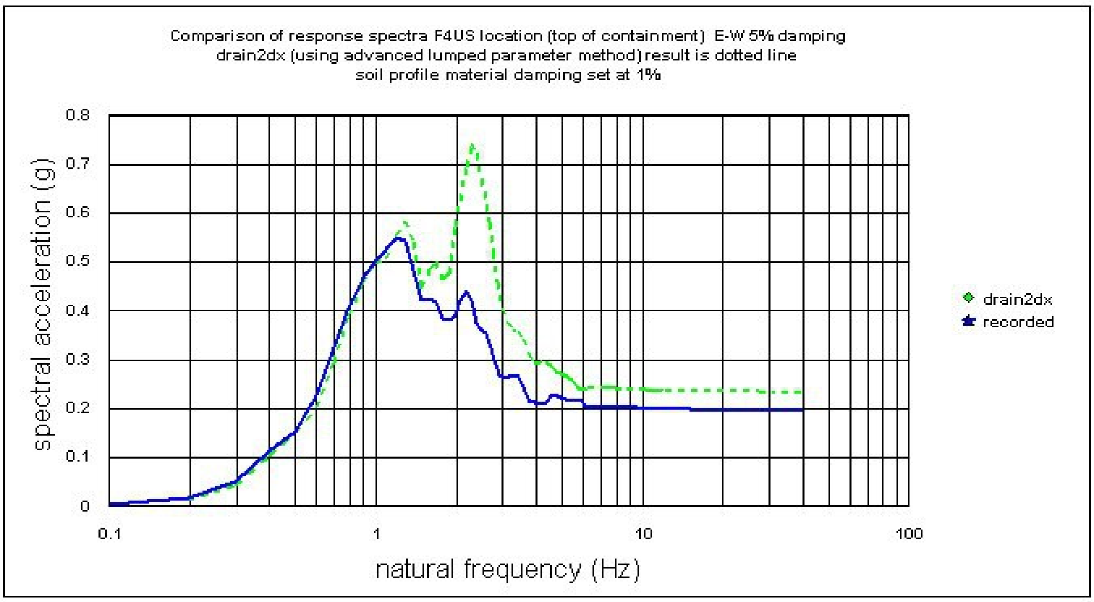
DRAIN2DX results

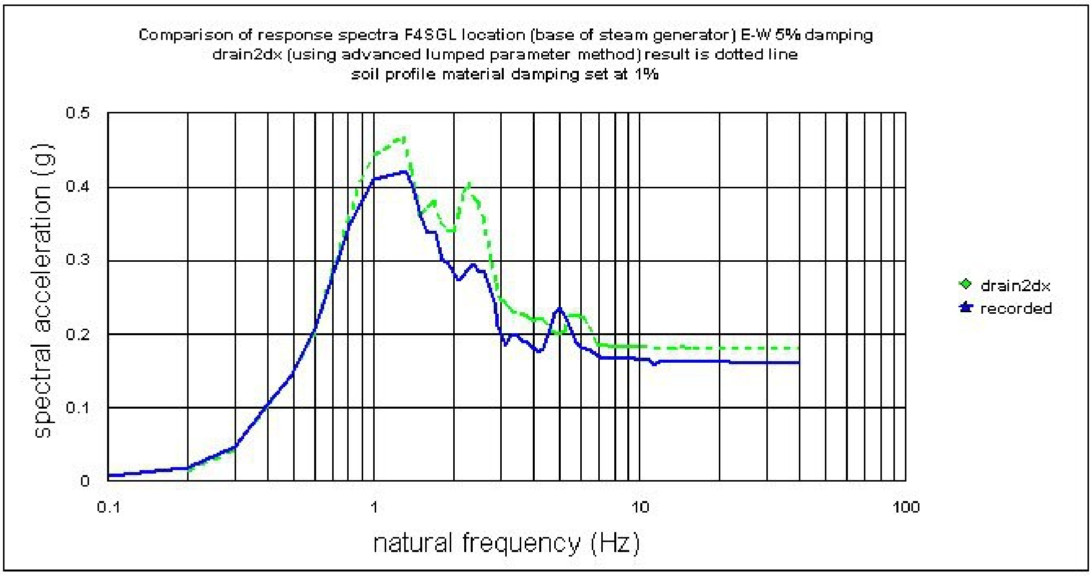
1% soil material damping case

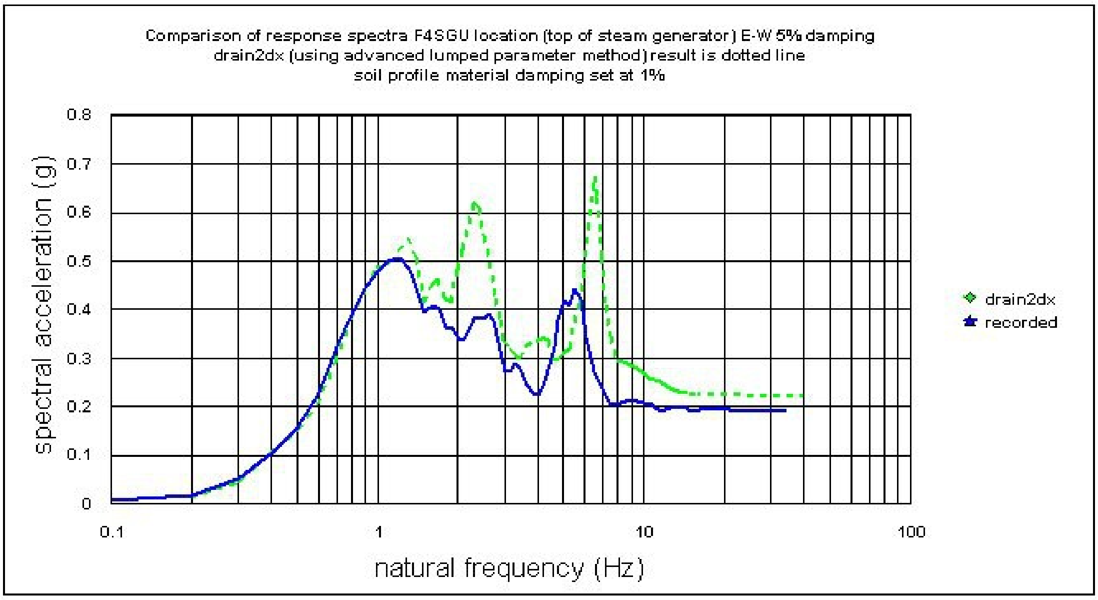
The modal analysis results for this case are 2.71 Hz (with 10.8% modal damping) for the SSI rocking mode, 6.55 Hz (with 1.9% damping) for the local horizontal vibration mode of the steam generator and 9.06 Hz (with 71.3% damping) for the SSI horizontal mode. The SSI modal results look reasonable. There is some discrepancy with SASSI regarding the natural frequency of the steam generator (which looks to be about 5.6 Hz from the response spectrum graph given in the manual) and this may be attributable to some rotational flexibility coming from the basemat. (In SASSI the basemat is modelled using brick elements and the internal structure stick model is connected by a set of very stiff beam elements at the top of the basemat.)

The in-structure response spectra are compared with experimental data at four locations digitised from graphs given in the SASSI2000 User Manual. The comparison is shown in the figures below and is anticipated to be closer than what would be obtained with more conventional versions of the lumped parameter method which attempt to represent an entire impedance function by a single spring and damper.







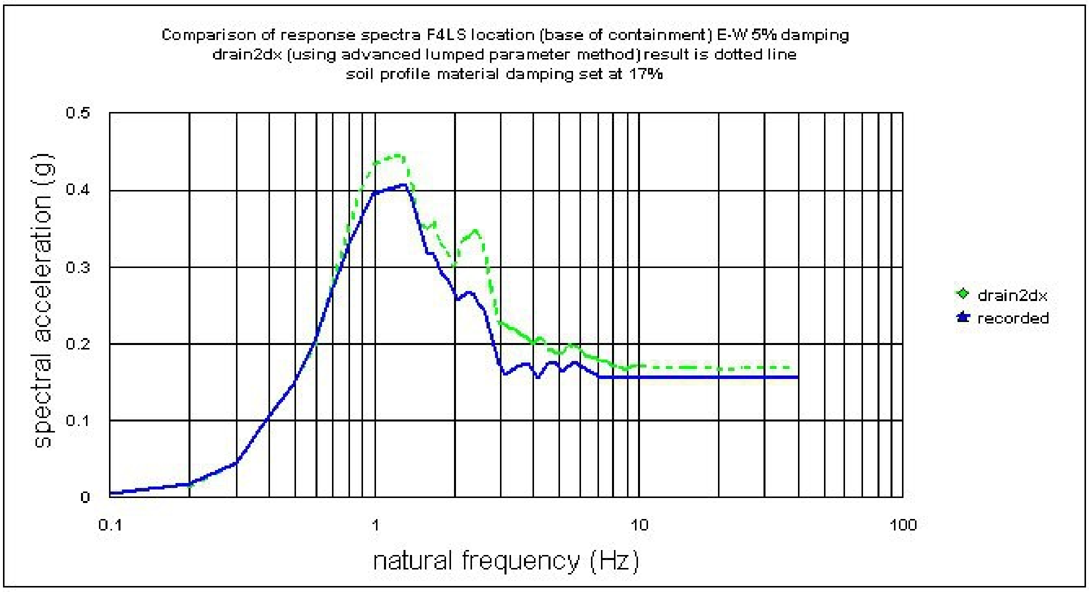


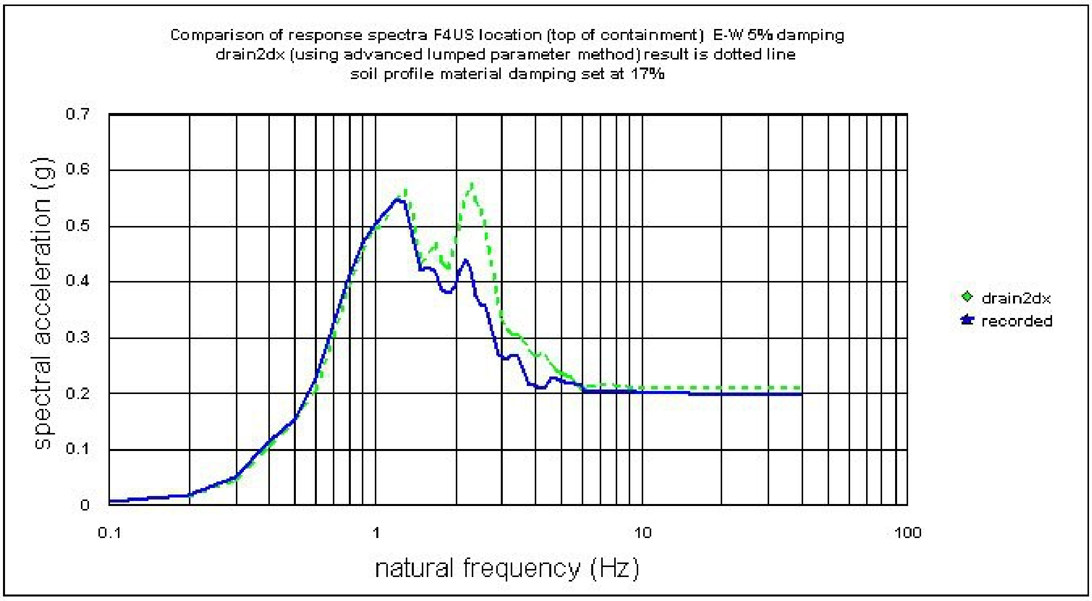
17% soil material damping case

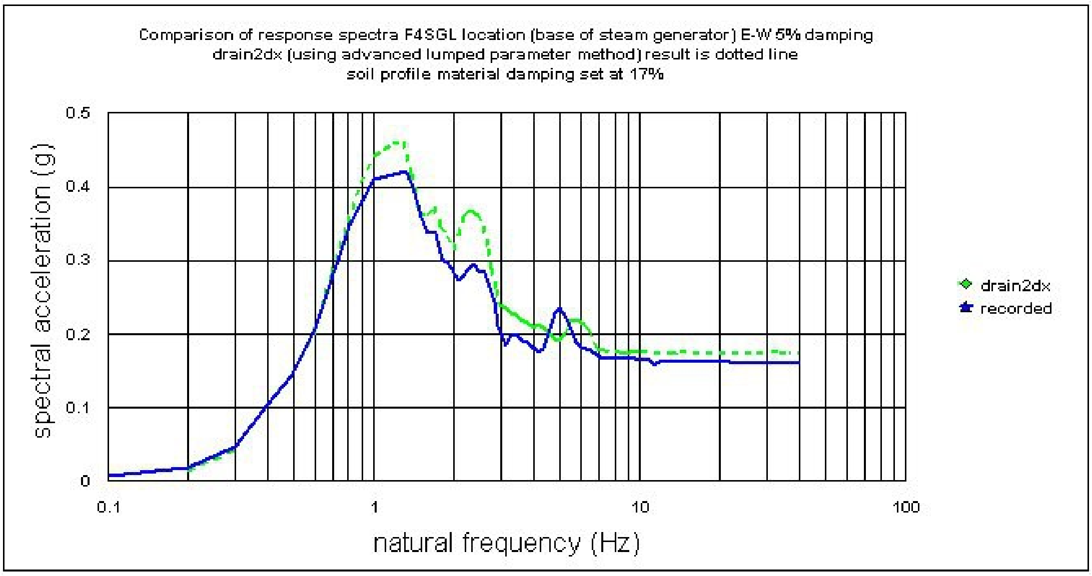
When the soil material damping is increased to 17% (the same value used in the SASSI 2000 example problem), the modal analysis results are changed to 2.35 Hz (with 151.2% damping) for the rocking SSI mode, 6.54 Hz (with 7.6% damping) for the local horizontal mode of the steam generator and 7.80 Hz (with 503.5% damping) for the SSI horizontal mode. The SSI natural frequencies should be very similar to the 1% soil damping case, and the discrepancy arises from static stiffness not being accurately represented in the curvefitting of the impedance functions. The SSI modal damping values, which are not actually used in the direct time history analysis performed by DRAIN2DX, are much higher than normally seen in a SSI analysis.

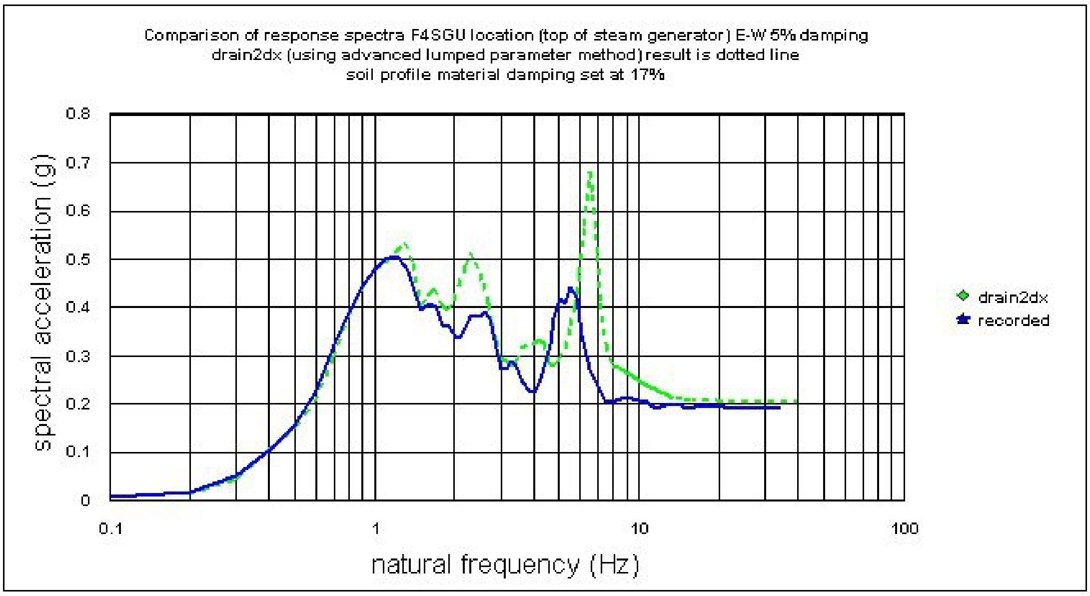
The in-structure spectra are compared with experimental results in the figures below. The DRAIN2DX results show impressive agreement with the experimental results, except for the high spectral peak predicted at the top of the steam generator (F4SGU) location. (This high spectral peak was also observed for the low soil material damping case, and the amplitude of this peak does not seem to be affected by the increase in SSI damping.) In figures given in the SASSI2000 User Manual, SASSI shows even better agreement with the experimental results and also gives close agreement for the spectral peak associated with the local vibration mode of the steam generator.

The good comparison with experimental results also suggests that the assumptions of full welded contact for the embedded foundation and being able to ignore the Khr coupling term are reasonable.







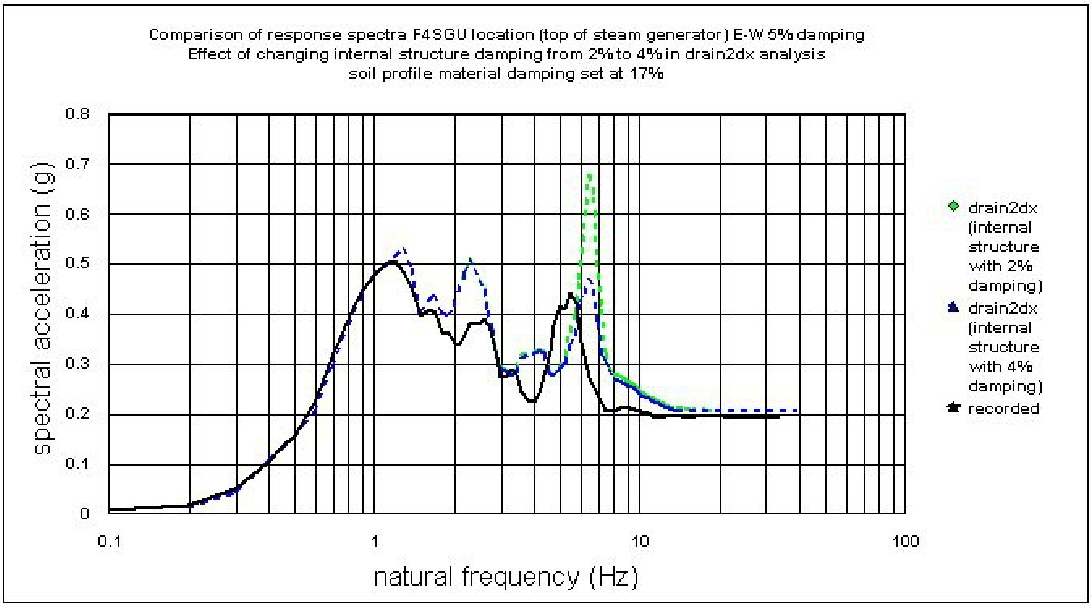


Investigation into improving result at top of steam generator location

A possible explanation for the high spectral peak at the top of the steam generator location calculated by DRAIN2DX is that in the experiment the structural damping associated with vibration of the internal structure is actually significantly higher than 2%.

The 2% damping value used for the internal structure, taken from the SASSI example problem, probably corresponds to something like ‘Stress Level 1’ in the ASCE 4 Standard, and may be based on interpreting the internal structure as being ‘equipment’. If the internal structure was classified as a ‘bolted steel structure’ (which may or may not be appropriate), a damping level of 4% could be claimed for ‘Stress Level 1’ conditions.

When the DRAIN2DX analysis was re-run with 4% structural damping assigned to the internal structure, the amplitude of the spectral peak at the top of the steam generator location shows improved agreement with the experimental result, as seen in the figure below.



References

1 SASSI2000 User Manual. A System for Analysis of Soil-Structure Interaction. Revision 1, November 1999

2 Gustavsen B., Semlyen A., "Rational approximation of frequency domain responses by Vector Fitting", IEEE Transactions on Power Delivery, Vol 14 No 3, July 1999